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# Sensitivity analysis to quantify uncertainty in Life Cycle Assessment: The case study of an Italian tile

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ABSTRACT

The results of a Life Cycle Assessment (LCA) study can be affected by several uncertainty sources, mainly due to the methodological choices, the initial assumptions, i.e. allocation rules, system boundaries and impact assessment methods, and the quality of the available data. Then, the experts should estimate the extent of the above-mentioned sources of uncertainty for improving the reliability and the representativeness of the obtained eco-profiles. To estimate the uncertainty is necessary to obtain reliable, transparent and representative LCA results and to correctly support decision-makers in the selection of different product or process options.

The following paper starts from a LCA study of the so-called "Sicilian tiles", which are typical roof tiles employed in restoring old buildings of the Mediterranean area. The authors identify the most relevant sources of uncertainty in the LCA study. Then a sensitivity analysis is performed to estimate the effects on the tile eco-profile of different secondary input data and of the chosen methods for the environmental impact assessment. The results show that, in some cases, significant differences in the energy and environmental indices can be obtained, pointing out the need of developing sensitivity analysis for strengthening the reliability of the obtained eco-profiles.



**Contents**



## 1. Introduction

Life Cycle Assessment (LCA) methodology is used to assess the resource consumption and the environmental impacts arisen from the life cycle of products and services [1]. Comprehensively, the goal of LCA is to support the development of low impact production systems and to provide decision makers with information on the environmental effects of different choices [2].

Nevertheless, LCA supported decisions may be misleading, because the results of a LCA study can be affected by different sources of uncertainty [3–5], mainly related to methodological choices, initial assumptions made on the allocation rules and system boundaries definition, and quality of the available data [6–9].

Essentially, uncertainty derives from missing knowledge on the exact value of a quantity [10].

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In detail, Huijbregts [11] distinguishes the following types of uncertainty:

- Parameter uncertainty, due to imprecise, incomplete, outdated or missing values of data needed in the inventory analysis or in the impact analysis.
- Models uncertainty, often due to the adoption of linear models to describe the relationships among environmental phenomena and of aggregate data regarding spatial and temporal features.
- Uncertainty due to unavoidable methodological choices in LCA, such as allocation methods, functional unit, system boundaries, cut-off rules, data collection methods.
- Spatial variability across location and temporal variability over a short and long time scales in the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) parameters.
- Variability between sources in LCI (e.g. variation in comparable technical processes) and between objects of the assessment in LCIA (e.g. human characteristics).

A significant source of uncertainty is the use of secondary input data. Thus, indicators of data quality are needed to express their representativeness, significance and reliability [10].

Indicators of data quality provide information for: age of data (year of the original measurement); geographical area and technological level; completeness and representativeness of data; reliability, depending on the methods used for measurements and calculations, assumptions and quality control of data [12,13].

In some cases, even if secondary input data have specific quality requirements, they are not able to describe appropriately the investigated system. Nevertheless, the life cycle analysts have to choose among these available data, founding their choices on considerations arisen by subjective experience and personal knowledge.

The selection of the method for the environmental impacts assessment involves uncertainty in LCA [13]. In fact, each method assesses impacts using different pollutant substances and characterization factors, but a unique correct choice does not exist. Thus LCA practitioners can only make subjective choices.

May et al. [2] introduce three procedures of analysis to estimate the uncertainty of LCA results: (1) gravity analysis to determine data with the highest contribution; (2) uncertainty analysis, which determines range of possible results based on data uncertainty; and (3) sensitivity analysis, which assesses the influence of a parameter (the independent variable) on the value of another (the dependent variable). In LCA studies, independent variables can be input data, system boundaries, allocation rules, model or process choices. Usually, dependent variables are output parameter values.

In the following sections, the authors present briefly the results of the LCA of the so-called “Sicilian tiles”, which are typical roof tiles used in the past and recently employed in restoring old buildings in the Mediterranean area, and highlight the most significant energy and environmental issues of the examined product.

Hence stated the main uncertainty sources, a sensitivity analysis is performed to assess the influence of the initial choices and assumptions on the tile eco-profile. In particular the authors assess the effects of: (1) the secondary data; (2) the Environmental Impact Assessment (EIA) methods; and (3) the characterization factors for the Global Warming Potential (GWP) calculation.

## 2. Case study

This section presents the eco-profile of a clay tile used in the Mediterranean building context and currently employed both in historical buildings and in new constructions. The assessed product is manufactured in a handicraft firm in Sicily (Italy) and is traditionally called “Sicilian tile”.

The following phases are included in the life-cycle analysis:

- resource (raw materials and fuels) supply and transportation to the site of production;
- production process (tile manufacture, drying and baking, and packaging);
- distribution.

Installation, use, maintenance and end-of-life steps have not been taken into account.

In the production process the raw materials, which are essentially clay, water, salt and sand, are mixed by an electrical kneader and the tiles are shaped manually. Then, the tiles are naturally dried for some days and baked in a biomass burner. The final products are selected, packed by pallets and PVC film and delivered to final users. Details on the life-cycle of the tile are described in [14]. Fig. 1 shows the flow chart of the examined production system.

The following primary data have been collected from an infield enquiry (reference year 2005):

- the consumption of raw materials (clay, water, salt and sand);
- the consumption of electricity and fuels (biomass and gas-oil) in the clay mining and in the tile production;
- the amounts of PVC and wood used in the packaging phase;
- the fuel consumption in the transportation of raw materials and fuels to the firm, and in the final product delivery.

Secondary data are derived by literature, such as the eco-profiles of electricity, gas-oil, biomass, raw materials and use of trucks [15].

The selected Functional Unit[1] (FU) is the production of 1000 kg of tiles [16]. The analysis is carried out following the ISO 14040 standards series [1,12].

Table 1 shows the eco-profile of the selected FU, while Fig. 2 illustrates the contribution of each step to the Global Energy Requirement (GER). The GER amounts to about 4367 MJ/FU, of which 19% is due to fossil sources and 81% to the renewable ones. The GER mainly arises from the baking phase (about 80.5% of GER) and it is essentially due to the biomass burning. Transportation, manufacture and packaging steps accounts for the 8%, 5% and 5.5% of the total GER, respectively. The lowest share comes from the clay mining, which is about the 1% of the total GER.

With regard to GWP, that amounts to about 58 kg $CO_{2\,\text{equiv.}}$, transportation involves the highest contribution (about 46%). The manufacture step shares for about 24%, the baking step for about 15%, while the packaging and clay mining for 10% and 5%, respectively.

## 3. Sensitivity analysis

### 3.1. Uncertainty of input secondary data

Generally secondary data, which are derived by referenced literature, are related to resources and emissions pertaining a specific process, with a specific technology and a specific production equipment. In the best cases metadata are added to secondary data to provide qualitative information, regarding for example system boundaries and allocation rules, to define if such data are able to characterise the investigated system.

To use secondary data involves uncertainty in a LCA study significantly. This essentially occurs because their accuracy and reliability, and their collection method may not be known [17].

[1] The Functional Unit (FU) is defined as the reference unit through which the performance of a product system is quantified in a LCA [1].

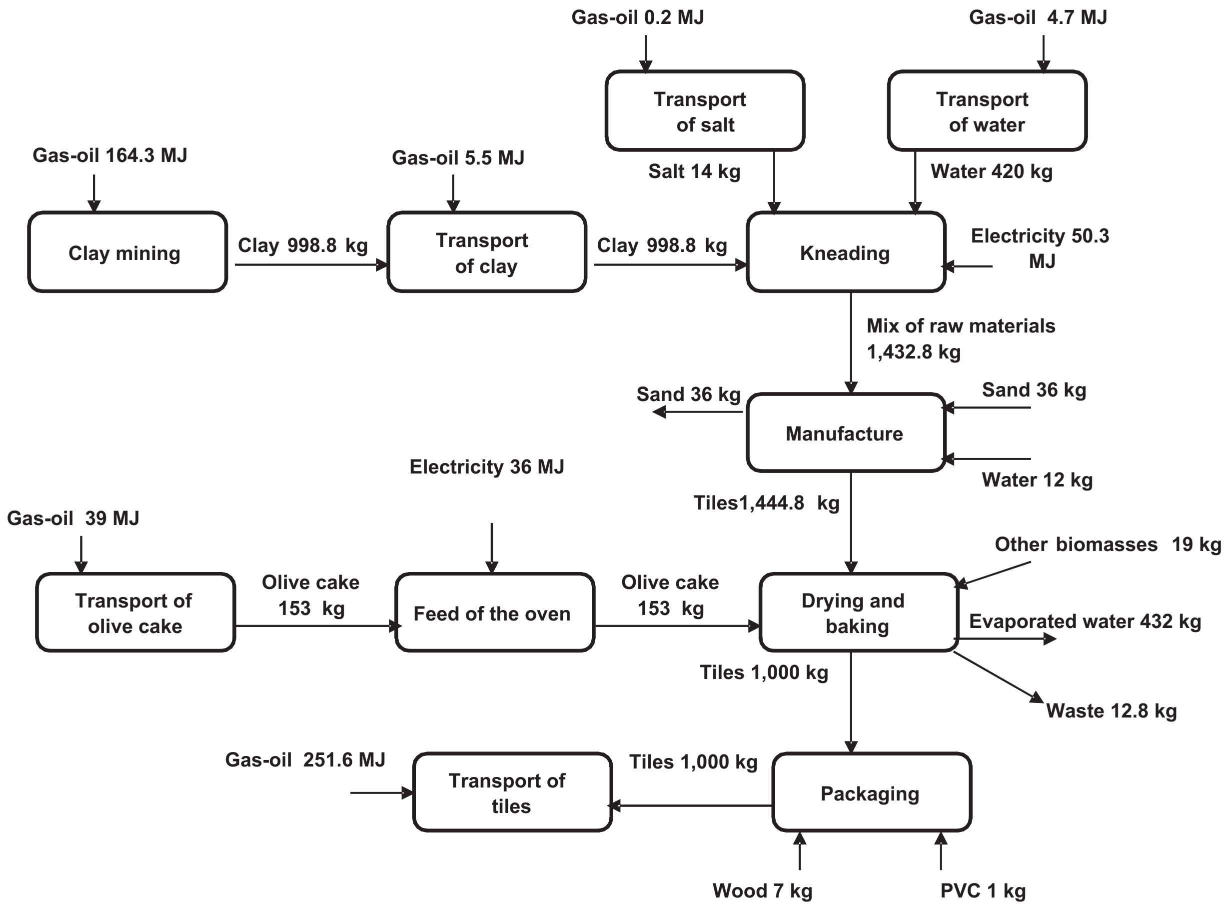



**Fig. 1.** Flow chart of the production of 1 FU.

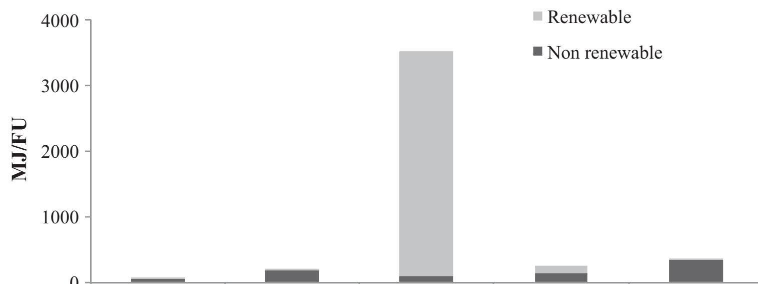
Huijberts et al. [18] highlight the significance of temporal, geographical and technological correlations between data used in the LCA study and data needed to represent the examined system.

The ‘temporal correlation’ represents the degree of accordance between the year of the study and the year of the available data. As some industrial technologies develop very quickly, the use of old secondary data in current studies can significantly distort the results.

The ‘geographical correlation’ represents the degree of accordance between the production conditions in the area of the study and those ones in the geographical area to which the secondary data are referred.

**Table 1**
Eco-profile of clay tile per FU.

| | Clay mining | Manufacture | Drying and baking | Packaging | Transports |
|---|---|---|---|---|---|
| **Resource use** | | | | | |
| Clay (kg) | 998.8 | 0.27 | 4E−03 | 0.03 | – |
| Gravel (kg) | 0.04 | 38.5 | 0.12 | 0.5 | – |
| Sodium chloride (kg) | 7.2E−04 | 14.2 | 3E−03 | 0.73 | – |
| Water (kg) | 11.7 | 1208 | 394 | 142 | – |
| Oil, crude (kg) | 0.85 | 2 | 1.32 | 0.27 | 7.8 |
| Coal (kg) | 0.09 | 2.2 | 0.90 | 0.70 | 0.14 |
| **Air emissions** | | | | | |
| $CO_2$ (kg) | 2.8 | 13.3 | 8.3 | 6.7 | 25.6 |
| CO (kg) | 0.01 | 8E−03 | 3E−03 | 6E−03 | 0.14 |
| $NO_x$ (kg) | 0.03 | 0.03 | 31.5 | 0.02 | 0.5 |
| $SO_x$ (kg) | 4.3E−03 | 0.08 | 0.4 | 0.02 | 0.04 |
| $CH_4$ (kg) | 2E−03 | 0.02 | 0.01 | 0.01 | 0.03 |
| **Water emissions** | | | | | |
| $BOD_5$ (kg) | 1.2E−03 | 4.1E−03 | 9.8E−06 | 2.1E−03 | 3.5E−05 |
| COD (kg) | 1.2E−03 | 7.5E−03 | 1.2E−04 | 3.3E−03 | 1.1E−03 |
| Solved substances (kg) | 5.8E−05 | 1E−03 | 5.6E−04 | 3.1E−03 | 1.5E−03 |
| Nitrate (kg) | 1.2E−04 | 5.8E−03 | 6.2E−5 | 1.1E−03 | 2.5E−04 |
| Sulphate (kg) | 9.9E−03 | 0.2 | 9.2E−03 | 0.1 | 7.3E−03 |
| **Waste** | | | | | |
| Mineral waste (kg) | – | – | 12.9 | 0.06 | – |
| Sand waste (kg) | – | 32.5 | – | – | – |
| GWP (kg $CO_{2\ equiv.}$) | 2.9 | 14 | 8.5 | 5.6 | 26.8 |




| | Clay mining | Manufacture | Drying and baking | Packaging | Transports |
|---|---|---|---|---|---|
| Renewable | 0,2 | 21,4 | 3418,9 | 110,6 | 0,4 |
| Non renewable | 43,9 | 188,1 | 102,6 | 131,5 | 349,6 |

**Fig. 2.** Global Energy Requirement.

The 'technological correlation' describes the representativeness of secondary data for a specific technology, company or process of production [11,13,16,17].

In the following sections the authors carried out a sensitivity analysis in order to assess the effects on the FU eco-profile by different secondary data. In detail, the following life-cycle phases are considered:

- *Transportation*. The extent of the variation on the FU eco-profile is estimated by using different databases and varying the features of the vehicles as type, age and load [19].
- *Electricity*. Different eco-profiles of electricity production in Italy are compared.
- *Baking step*. Variation of the results is assessed by using different literature data on air emissions from the combustion of biomass.

### 3.1.1. Transportation

Secondary data are derived from international databases to assess the environmental impacts related to the road haulage. The selection of a suitable eco-profile for truck is quite hard, due to the changing system boundaries or technologies used when comparing different databases. For instance, some of these databases include steps as the infrastructure construction (road, bridges and tunnels), the production of the truck, the direct energy consumption and the emissions during operation, the end-of-life, and the waste generation [15], while other databases provide only data related to the direct emissions by truck. Further other databases do not provide any information about the included system boundaries or other information.

A scenario analysis is carried out to compare different truck eco-profiles. In detail, the following scenarios are examined:

- *Base Scenario* [15,20]: road transport by diesel-truck, average load 50%, includes production and combustion of fuels. Trucks with capacity of 16 tons are used for the transportation of clay, salt, water, sand and mineral wastes to landfill; olive cake and tiles are delivered by trucks with capacity of 28 tons and 40 tons, respectively;
- *Scenario 1* [15,21]: inventory analysis includes construction of the infrastructures (roads, bridges and tunnels), manufacturing of the truck, direct energy and working material consumption and emissions during operation. The trucks used for transportation are those assumed in the Base Scenario;
- *Scenario 2* [22]: diesel trucks of 14–20 tons are used to transport raw materials and mineral wastes, trucks of 20–28 tons to transport olive cake, and truck with semi-trailer to transport the tiles;
- Scenario 3 [23]: trucks of 4 tons are used to transport sand, water and salt, trucks of 9 tons to transport clay and mineral wastes to landfill, articulated of 13–14 tons to transport olive cake and tiles.

From a comparison of the previous scenarios, Scenario 1 involves the highest environmental impacts (Fig. 3). In detail, GER increases of almost 95% and GWP of almost 52%, in comparison with the Base Scenario. This is essentially due to the inclusion of the infrastructure construction step in the eco-profile of the trucks in Scenario 1. In the Scenario 2 and 3 the variations of GWP and GER are lower than 25%. Relevant variations (>100%) occurred for the Ozone Depletion Potential (ODP) impact in all the assessed scenarios. In Scenario 1 Acidification Potential (AP) variation is less than 2.5%, while for Scenario 2 and 3 the corresponding variations are about 50%. With regard to Eutrophication Potential (EP), variations of about 23%, 50% and 67% are respectively in Scenarios 1, 2 and 3. Photochemical Ozone Creation Potential (POCP) has the lowest variation in the Scenario 1 (6.5%), while the highest variations are in Scenario 2 and 3 (83% and 88%, respectively).

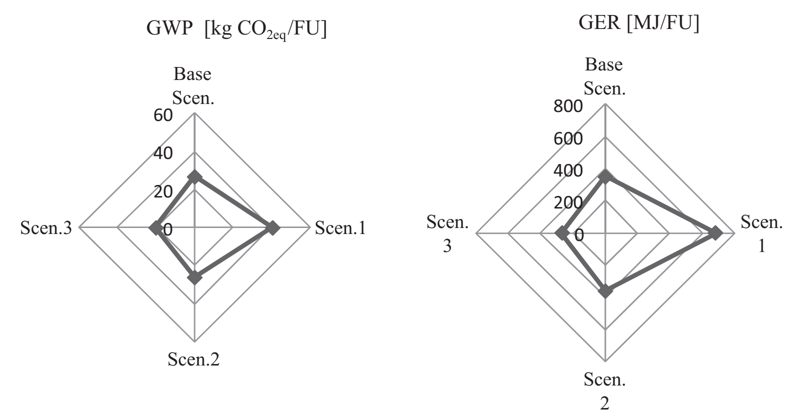
No information about the system boundaries is provided in the Base Scenario and in Scenarios 2 and 3. Thus, it is quite hard to compare the related results. The differences among the examined Scenarios could be due to the different amounts of fuel needed to cover a distance and/or to the different emissions from the fuel combustion, depending to engine's technology.

### 3.1.2. Electricity

Electricity consumption for the production of the tile (about 86 MJ) is essentially due to the kneader, to the electric machine used to feed the oven, and to the space lighting. Such a consumption involves a primary energy consumption of 275 MJ (6.3% of GER).

The authors estimate the uncertainty arising from the choice of the electricity eco-profile, taking into account the following scenarios:

- *Base Scenario*: ETH-ESU 96 database [15,21]: inventory table includes domestic low voltage electricity supply, imports, transport and transformation losses as well as material and construction requirements for transmission and distribution. Country mix is referred to a five years average (1990–1994). Contributions of renewable energies such as wind power, geothermal power and photovoltaic are considered in addition to the hydro-electric power.
- *Scenario 1*: Ecoinvent database [15]. It includes the electricity production in Italy and imports, the transmission network, direct $SF_6$-emissions to air and electricity losses during low-voltage transmission and transformation from medium-voltage. Average




| Environmental Impact | Base Scenario | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|---|
| GER [MJ] | 350 | 683 | 364 | 268 |
| GWP [kg $CO_{2eq}$] | 26.8 | 40.5 | 26.0 | 20.1 |
| ODP [kg CGC-$11_{eq}$] | 2.0E-05 | 4.9E-05 | 9.0E-11 | 0 |
| AP [kg $SO_{2eq}$] | 0.27 | 0.28 | 0.15 | 0.14 |
| EP [kg $PO4^{3-}{}_{eq}$] | 0.06 | 0.05 | 0.03 | 0.02 |
| POCP [kg $C_2H_{4eq}$] | 0.17 | 0.18 | 0.03 | 0.02 |

**Fig. 3.** Comparison of different transport scenarios (transport step).

technology is used to distribute electricity. The time period is not specified.
- *Scenario 2*: Boustead Model database [23]: the electricity eco-profile is referred to the Italian energy mix (year 1996), no detail for the voltage is provided.

From the comparison of the above scenarios, it is possible to observe that the variations of GER, AP and EP results are negligible (<1%), and the variation of GWP is lower than 8%. The variation of POCP goes from −4.5% (Scenario 2) to 13.5% (Scenario 1), while ODP has a variation of about 40% (Fig. 4).

**Table 2**
Chemical properties of olive cake.

| Chemical properties | Values | |
|---|---|---|
| | Min (%) | Max (%) |
| Carbon (C) | 38 | 47.88 |
| Hydrogen (H) | 4 | 7.14 |
| Sulphur (S) | 0.01 | 0.6 |
| Oxygen (O) | 20 | 36.7 |
| Nitrogen (N) | 0.68 | 4 |
| Dry ash | 2.56 | 12 |
| Moisture | 7 | 21 |

### *3.1.3. Baking step*

The baking step takes place in a traditional furnace fed by "olive cake"[2], a waste biomass of the Mediterranean olive oil production process [26].

Due to the lack of information on the eco-profile of the olive cake, some energy and environmental features have been derived by literature sources.

Depending on the literature source the heating value of such a biomass varies from 17.8 MJ/kg [26–30].

Looking at the chemical properties of the olive cake (Table 2), it can be noted the presence of slight traces of sulphur, that makes this product a clean fuel [26,31–33].

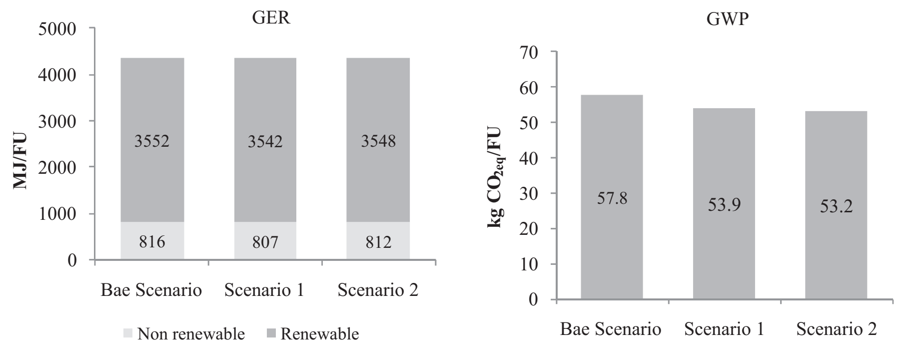
Armesto et al. [34] assessed the emissions from the co-firing of olive oil waste and coal concluding that $SO_2$ and $NO_x$ emissions are not affected by the use of olive oil waste in the fuel-mix. Al-Widyan et al. [30] observed that $SO_2$ and $NO_x$ concentrations are much less than those emitted from similar solid waste like charcoal. Topal et al. [29] studied the olive cake combustion in a fluidized bed and stated that $NO_x$ emissions (based on 7% of $O_2$) are quite low and $SO_2$ emissions are negligible.

Table 3 shows the results of the experimental analysis carried out by Nicoletti et al. [32,33] to assess the emissions from olive cake combustion.

Starting from literature data on the heating value and emissions, the following sensitivity scenarios are compared:

- *Base Scenario*: heating value: 19.9 MJ/$kg_{fuel}$; emissions from Table 3, experiment 1;
- *Scenario 1*: heating value: 17.8 MJ/$kg_{fuel}$; emissions from Table 3, experiment 1;
- *Scenario 2*: heating value: 22.14 MJ/$kg_{fuel}$; emissions from Table 3, experiment 1;
- *Scenario 3*: heating value: 19.9 MJ/$kg_{fuel}$; emissions from Table 3, experiment 2.

[2] Oil, water and wet olive husks are the products obtained from the olive processing. Olive husks contain an approximate 5–8% in weight of residual oil, 20–60% of water and 62–75% of solid matter.ecause <fn0015>of the high percentage of oil still retained, husks undergo a further chemical treatment with the aid of a solvent. The process allows a further extraction of oil and the production of a waste biomass called "olive cake", characterized by low humidity [24,25].




| Environmental Impact | Base Scenario | Scenario 1 | Scenario 2 |
|---|---|---|---|
| ODP [kg CFC-11$_{eq}$] | 3.6E-05 | 2.1E-05 | 2.2E-05 |
| AP [kg $SO_{2eq}$] | 16.5 | 16.4 | 16.6 |
| EP [kg $PO_4^{3-}{}_{eq}$] | 4.17 | 4.19 | 4.18 |
| POCP [kg $C_2H_{4eq}$] | 0.22 | 0.19 | 0.23 |

**Fig. 4.** Comparison of different electricity eco-profile.

**Table 3**
Pollutants caused by olive cake combustion.

| | $H_2O$ (kg/kg) | $CO_2$ (kg/kg) | $NO_x$ (kg/kg) | $SO_2$ (kg/kg) | Dust (kg/kg) |
|---|---|---|---|---|---|
| Experiment no. 1 | 0.3 | 0.004 | 0.2 | 0.002 | 0.25 |
| Experiment no. 2 | 0.3 | 0.003 | 0.2 | 0.02 | 0.2 |

The air emissions included in the impact assessment are referred only to biomass combustion, while air emissions due to its production have not been taken into account.

In the scenario analysis, Scenario 3 does not affect GER, while Scenario 2 has not an influence on the environmental impacts of FU.

By varying the heating value of the olive cake from the lowest to the highest, the primary energy requirement in the baking step varies from 3188 MJ/F.U. (Scenario 1) to 3855 MJ/F.U. (Scenario 2). While the contribution by non-renewable sources (102.6 MJ/F.U.) is unvaried, the contribution of renewable energy has a variation of about 9.8% with respect to the Base Scenario (Fig. 5).

Regarding the environmental impacts, from Table 4 it can be noted that the variation range is quite large. In fact EP, ODP and GWP does not vary significantly, while POCP has a huge variation (433%), mainly due to the significant differences in the amount of the $SO_x$ emissions changing from one scenario to another.

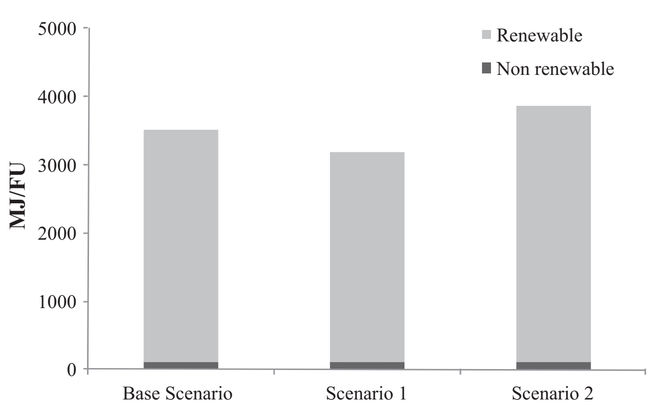



**Fig. 5.** Global Energy Requirement (baking step).

### 3.2. Uncertainty due to impact assessment methods

LCIA includes the following steps [1,12]:

- selection of impact categories, indicators and characterization factors;
- initial aggregation of data from inventory studies into the selected environmental impact categories (classification);
- assessment of the impact wideness within each of the classification category using specific characterization factors (characterization).

The selection of the impact method and the evaluation of impact categories involve uncertainty in the LCIA procedure.

Several methodologies are available for carrying out a LCIA and many of them are implemented in commercial software.

**Table 4**
Environmental impacts caused by olive cake combustion.

| Environmental impact | Base Scenario | Scenario 3 | Variation |
|---|---|---|---|
| AP [kg $SO_{2\,equiv.}$] | 16.1 | 18.9 | 17% |
| EP [kg $PO_4{}^{3-}{}_{equiv.}$] | 4.09 | 4.09 | 0% |
| GWP [kg $CO_{2\,equiv.}$] | 8.69 | 8.54 | −1.7% |
| ODP [kg CFC-11$_{equiv.}$] | Negligible | Negligible | – |
| POCP [kg $C_2H_4$] | 0.03 | 0.16 | 471.4% |

Sometimes, LCA practitioners simply select a LCIA methodology provided as part of a LCA software tool. In this case, impact categories, indicators, classification and characterization methods are preselected for the users. However, the choice of the LCIA method largely affects the final results [35].

The authors assessed the impact categories of AP, ODP and POCP using the following impact assessment methods:

- EPD 2008 (Base Scenario used in the case study): it is used for Environmental Product Declarations (EPD) following the recommendations of the Swedish Environmental Management Council. All impact categories are taken directly from the CML 2 baseline 2000 method [15].
- CML 2 baseline 2000 (Scenario 1): it is an update of the method reported in the Dutch Guide to LCA, published in 1992 by the Centre of Environmental Science (CML) [36]. The characterization model for ozone depletion defines the ODP of different gases (kg CFC-11 equiv./kg emission) at global scale, with an infinite time span. The POCP is calculated with the UNECE Trajectory model (including fate), and is expressed in kg $C_2H_4$ equiv./kg emission, with a time span of 5 days; the geographical scale varies between local and continental scale. The AP for emissions in air is calculated with the adapted RAINS 10 model, describing the fate and deposition of acidifying substances; the impact for every substance is expressed as kg $SO_2$ equiv./kg emission; the time span is infinity and the geographical scale varies between local and continental scale.
- Ecoindicator 95 (Scenario 2): it was developed according with CML 92 method. ODP values were established mainly for hydrocarbons containing combined bromine, fluorine and chlorine, or CFCs. One of these substances (CFC-11) was adopted as a reference. The POCP values are published for a wide range of volatile organic substances. The AP is expressed relatively to the acidifying effect of $SO_2$; other known acidifying substances are $SO_x$ (that has been added with the same value of $SO_2$), nitrogen oxides and ammonia [36].
- EDIP/UMIP 97 (Environmental Design of Industrial Products, in Danish UMIP) (Scenario 3). It was developed in 1996. The OPD was based on the status reports (1992/1995) of the Global Ozone Research Project. POCP values were taken from UNECE reports (1990/1992) and depend on the background concentration of $NO_x$ [36,37].
- IMPACT 2002+ (Scenario 4): it was developed by Swiss Federal Institute of Technology, Lausanne (EPFL). The methodology proposes the implementation of a combined midpoint/damage approach, linking all types of LCI results (elementary flows and other interventions) via 14 midpoint categories to four damage categories. This takes advantages both from midpoint-based indicators such as CML and from damage based methodologies as Eco-indicator 99. The characterization factors for the examined impact categories are adapted from existing characterizing methods, i.e. Eco-indicator 99 and CML 2001 [37,38].

From a comparison of the above five scenarios the following considerations can be done (Table 5):

- With regard to AP, in comparison with Base Scenario, Scenario 1 involves negligible increase (<1%), while Scenarios 2, 3 and 4 involve an increase of about 39%. The same characterization factors are used in Ecoindicator 95, EDIP/UMIP 97 and IMPACT 2002+ but some substances, as hydrogen sulphide, phosphoric acid, ammonia, ammonium carbonate, ammonium nitrate and ammonium ion, are accounted for only in one or two of these methods. Base Scenario and Scenario 1 differ for the emissions factors of $SO_2$ and $SO_x$ and for the inclusion of the nitric oxide as an acidifying substance in the second one.
- The ODP maintains the same order of magnitude in each scenario. However Scenario 2 results the most influencing one, involving an increase of about 48% in comparison with the Base Scenario. This is due to higher characterization factors used by Ecoindicator 95. All examined methods use different substances and characterization factors. Moreover, the IMPACT 2002+ computes more substances than the other methods.
- All the scenarios reduce POCP more than 50% in comparison with the Base Scenario. Even if CML 2 baseline 2000 and EPD 2008 involve the same emissions factors, however these methods account for different substances. The other methods employ different characterization factors and take into account different substances.

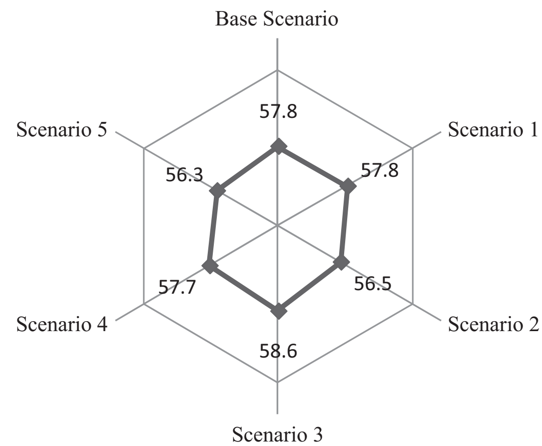



**Fig. 6.** Global Warming Potential [kg $CO_{2\ equiv.}$].

### 3.3. *Uncertainty due to the $CO_2$ characterization factors for Global Warming Potential*

The authors carry out a scenario analysis to assess the effect on the FU eco-profile by changing the method used to calculate GWP. In particular, the following scenarios are compared with the Base Scenario:

- Scenario 1: CML 2 baseline 2000;
- Scenario 2: Ecoindicator 95;
- Scenario 3: EDIP/UMIP 97;
- Scenario 4: IPCC 2007;
- Scenario 5: Impact 2002+.

The methods used in the Scenarios 1, 2, 3 and 5, have been described in the previous section.

The IPCC 2007 method (Scenario 4) implements the characterization factors proposed by Intergovernmental Panel on Climate Change (IPCC). The same characterization factors are used for fossil and biogenic emissions. The radiative forcing due to emissions of $NO_x$, water, sulphate, etc. in the lower stratosphere and in the upper troposphere and the direct formation of dinitrogen monoxide ($N_2O$) from nitrogen emissions are not assessed. [39,40] (Jungbluth et al., 2004) (Prè, 2010).

As Fig. 6 shows, the differences among the compared scenarios result lower than 2.5%. The variation range of GWP goes from 56.3 kg $CO_{2\ equiv.}$ (Scenario 5) to 58.6 kg $CO_{2\ equiv.}$ (Scenario 3).

**Table 5**
Environmental impacts calculated by five different impact methods.

| Environmental impact | Base Scenario | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|---|---|---|---|---|---|
| AP [kg $SO_{2\ equiv.}$] | 16.52 | 16.63 | 22.93 | 22.93 | 22.93 |
| ODP [kg CFC-$11_{equiv.}$] | 3.6E−05 | 4.1E−05 | 5.3E−05 | 4.1E−05 | 4.0E−05 |
| POCP [kg $C_2H_4$] | 0.222 | 0.031 | 0.08 | 0.084 | 0.117 |

## 4. Synthesis of the results

The performed sensitivity analysis shows that in some cases there is a strong dependence of the FU eco-profile from different choices and assumptions related to secondary data and environmental impact assessment methods.

In detail, it has been estimated that:

- GER can vary from 4040 MJ to 4700 MJ, with a variation range of about ± 7.6% from the referring value of 4367 MJ.
- GWP has a variation range from the referring value (57.8 kg $CO_{2\ equiv.}$) that goes from −11.6% to 24%. In particular, GWP value can vary from 51.1 kg$CO_{2\ equiv.}$ to 71.5 kg$CO_2$.
- Regarding AP, a variation from 16.39 kg $SO_{2\ equiv.}$ to 22.93 kg $SO_{2\ equiv.}$ has been observed; the gap from the reference value (16.52 kg $SO_{2\ equiv.}$) goes from −0.8% to 39%.
- EP is characterized by a low variation (from 4.13 kg $PO_4{}^{3-}{}_{equiv.}$ to 4.19 kg $PO_4{}^{3-}{}_{equiv.}$) with respect to the Base Scenario (4.17 kg $PO_4{}^{3-}{}_{equiv.}$); the variation range is of about −1% to 0.5%.
- A considerable variation is attributable to POCP, that can vary from 0.031 kg $C_2H_{4\ equiv.}$ to 0.352 kg $C_2H_{4\ equiv.}$ with a variation range of about −86% to 59% from referring value of 0.222 kg $C_2H_{4\ equiv.}$.
- A relevant variation (from −56% to 81%) is also concerning the range of ODP. The absolute ODP value can vary from 1.6E−05 kg CFC-$11_{equiv.}$ to 6.5E-05 kg CFC-$11_{equiv.}$ whit respect to the reference value of 3.6E-05 kg CFC-$11_{equiv.}$

With regard to the contribution of the above scenario analyses, the obtained results are summarized in the following.

Sensitivity analysis of transportation secondary data has shown a variation for all the environmental impacts with respect to the Base Scenario. In particular, GER vary from −23% to 95%, GWP from −3% to 52%, AP from −48% to 2.5%, EP from −67% to −23%, POCP from −88% to 6%. Relevant variations (from −100% to 150%) occur for ODP impact.

Comparing different electricity eco-profiles, the variations of GER, AP and EP with respect to the Base Scenario are negligible (<1%), the variations of GWP, ODP and POCP are respectively lower than 8%, 43% and 11%.

Using different secondary data of biomass emissions during the baking step, it can be observed that GER varies of about 10% with respect to the Base Scenario, EP and ODP are the same in each examined scenario, while the other impacts have a quite extended range of variation, which goes from 1.7% (GWP) to 433% (POCP).

In the sensitivity analysis of impact assessment methods the environmental impacts vary from 39% (AP) to 86% (POCP) if compared with those of the Base Scenario, while in the sensitivity analysis related to GWP, this indicator has a variation lower than 2.5%.

## 5. Conclusions

A significant problem affecting the application of LCA concerns the uncertainty of the results, due to subjective choices mainly related to secondary data used in life cycle inventories or to impact assessment methods.

These subjective choices are influenced by personal experiences and knowledge, that leading to different choices of methods and tools by different people [41].

It is important to know to what extent the results of a LCA are affected by uncertainty, because it may be helpful for decision makers in judging the significance of the differences in product comparisons and options for product improvements [18,42].

The quantification of the uncertainty of the LCA final results is a crucial issue for the reliability of the methodology and an important step toward reliable and transparent decision support. It can be made through the sensitivity analysis, a procedure to determine how changes in data and methodological choices affect the results of the study [12].

As showed in the present paper, the FU eco-profile can be influenced significantly by different choices related to secondary input data and environmental impact assessment methods.

In order to reduce the uncertainty due to secondary input data, local databases containing site-specific data and related data quality indicators should be realized. This requires an effort by local firms, that should be willing to furnish primary data related to their productive processes; by policy makers, that should stimulate the local producers to carry out LCA studies of their products; and by LCA experts, that should assess the energy and environmental performances of local products and implement these in specific databases, following a specific data format.

Furthermore, to correctly support the LCA practitioners to reducing uncertainty due to other subjective choices and to perform LCA studies in accord to specific methodological choices and conventions, beginning from the results of experiences and projects already made, the scientific community needs to define harmonized and standardized rules related to the modelling of a product system, the allocation phase, the system boundaries, the impact assessment methods, the quality requirements for data used in the studies, and all other elements that can be source of uncertainty [11].

In this contest, the European Commission [43] realized the International Reference Life Cycle Data System (ILCD) Handbook, that represents a technical guidance document on recommended LCA practice in data collection, modelling, analysis, interpretation, documentation and review. ILCD is a useful tool to support the LCA practitioners and to provide a common basis for consistent and quality-assured life cycle data and robust studies.

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